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MODELING OF PULSED THERMOGRAPHY IN ANISOTROPIC MEDIA

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Materials Division, Patuxent River MD, 20670

Thermal Wave Imaging, Inc.
18899 W. 12 Mile Rd.
Lathrup Village, MI 48076

A simple thermographic model has been developed that accurately describes the surface temperature response of an aluminum panel with flat bottom holes of different depths and diameters to a short heat pulse. This model assumed that a thin layer of material at the surface is instantaneously heated by the pulse, and that subsequent cooling of the surface is due to diffusion of the deposited energy into the bulk of the material. The model accounts for sample thickness, density, specific heat, in-plane and out-of-plane thermal conductivity and defect size and depth. However, heat pulse parameters such as pulse duration and intensity were not included. In this talk we will present experimental and modeling results on graphite epoxy composites with flat bottom holes of different radii and depth. The experimental results were collected with standard pulse thermographic equipment. The experimental data was analyzed with our model. The effects of anisotropy in the thermal conductivity will be presented and discussed.

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to be presented at the
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MODELING OF PULSED THERMOGRAPHY IN ANISOTROPIC MEDIA

By:

Dr. Ignacio Perez
Paul Kulowitch
Rachel Santos
Steven Shepard

NAVAL AVIATION SYSTEMS TEAM

OUTLINE

NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

- EXPERIMENTAL
- DATA ANALYSIS
- SIMPLE CALORIMETRIC MODEL
- SIMPLE FINITE ELEMENT MODEL
- EXPERIMENTAL RESULTS
- SUMMARY AND CONCLUSION

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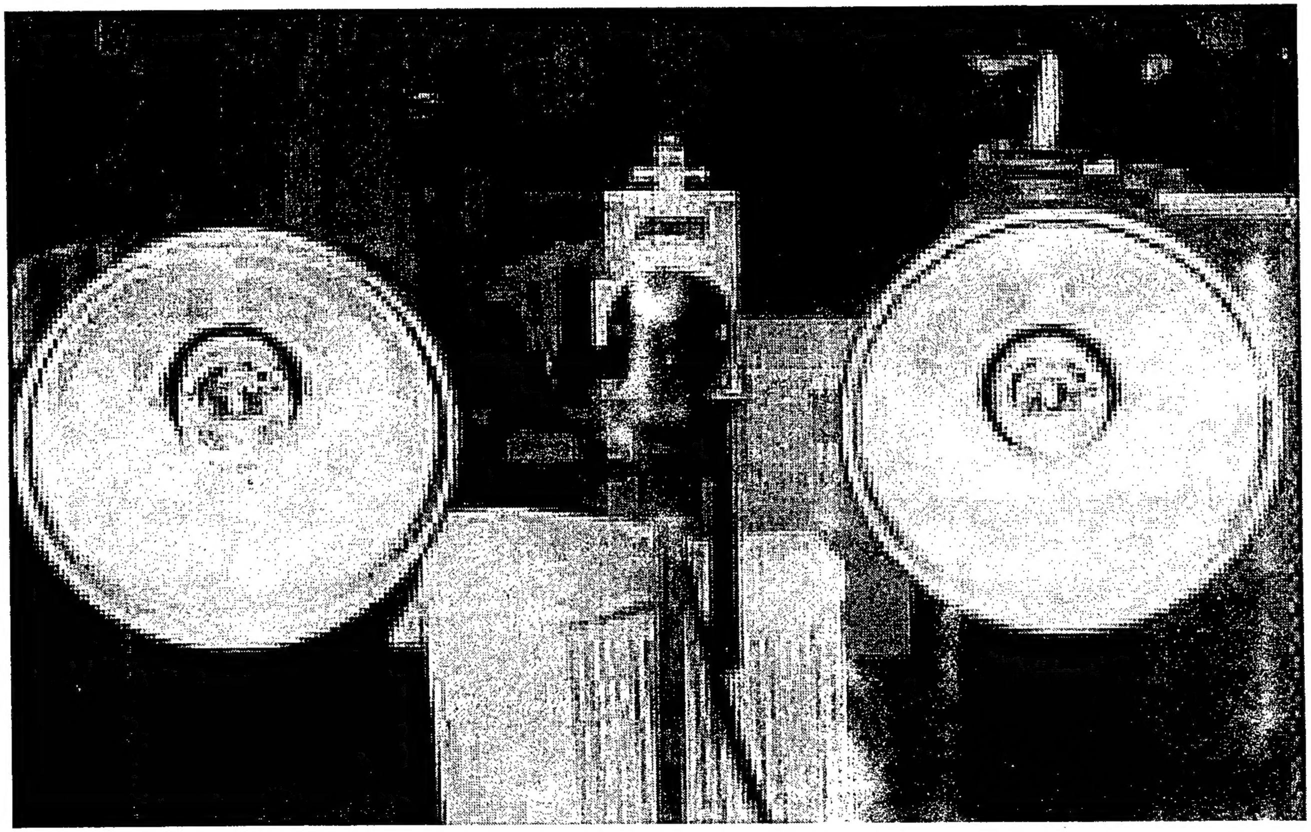
THERMOGRAPHIC SYSTEM

NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

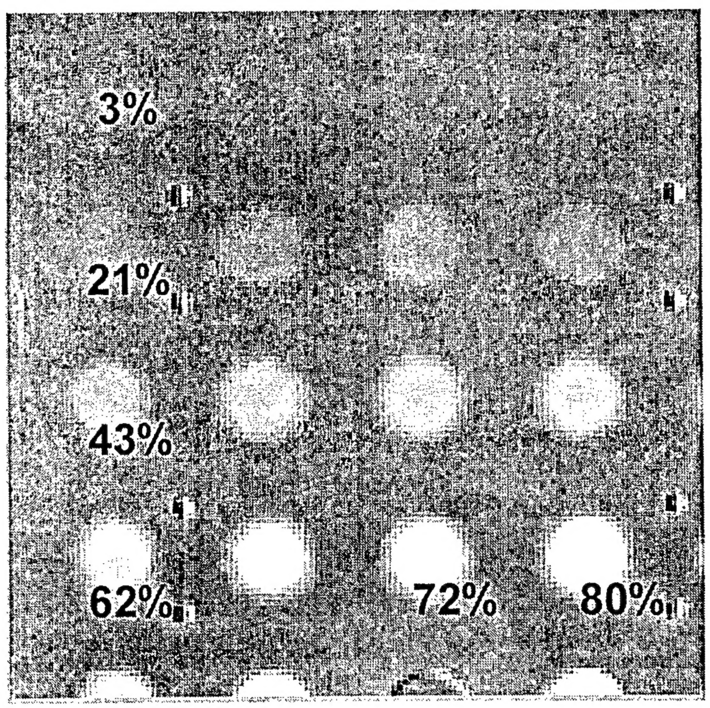


CAMERA SPECIFICATIONS
Amber Engineering Model AE-4128
128X128 InSb FPA
207 frames/s (max)
Sensitive to 0.01°C

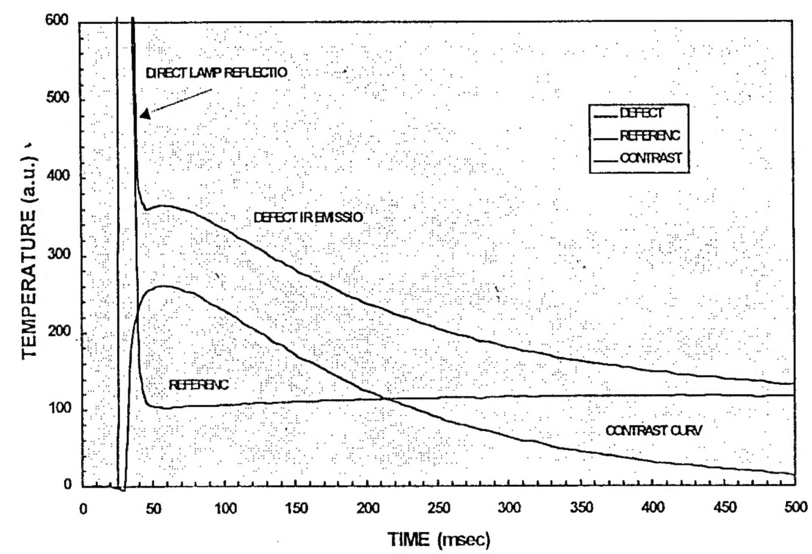
FLASH LAMP SPECIFICATIONS
Speedtron Model 4803CX Capacitors
Speedtron Model 206VF Lamps
Delivers 5KJ per lamp (2) in 5 ms

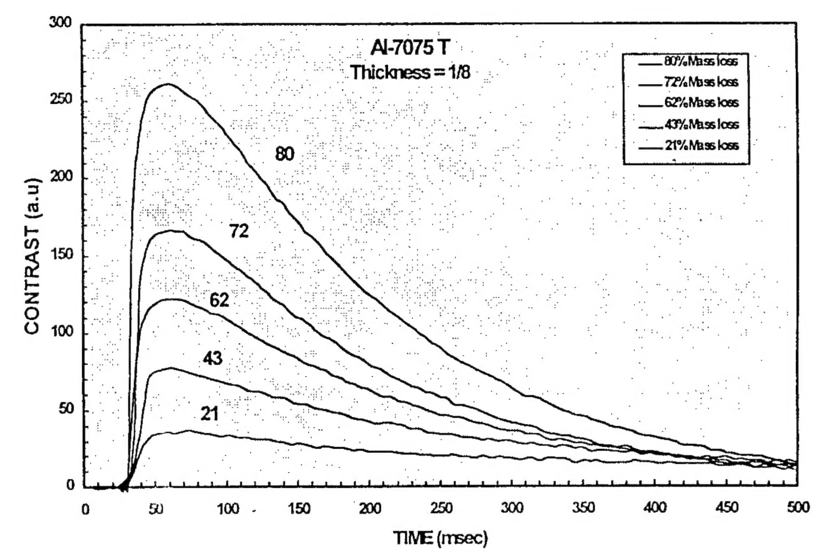
TEST PANEL & TYPICAL TIME-RESPONSE CURVES

1/8" Thick Al-7075 panel



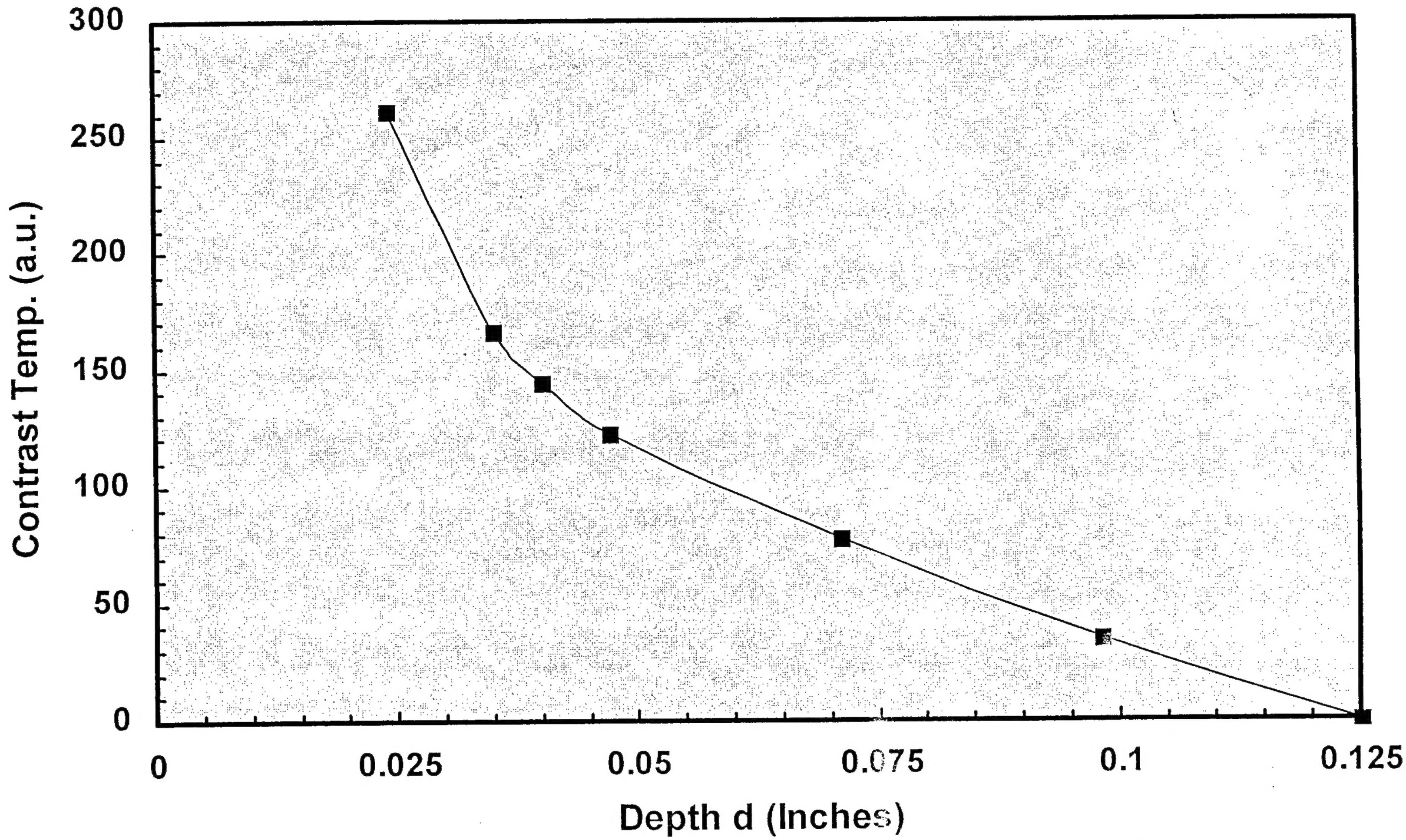
1" Diameter Holes





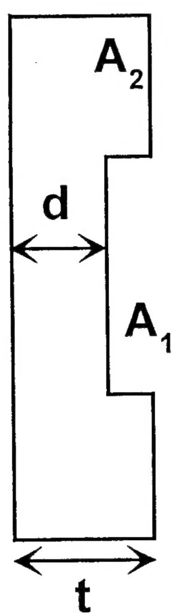
EXPERIMENTAL DATA

CONTRAST vs DEPTH

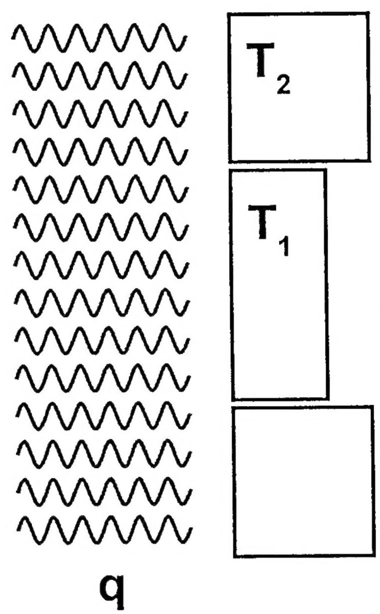


NO LATERAL HEAT CONDUCTIVITY APPROXIMATION

FLAT BOTTOM HOLE



NO LATERAL CONDUCTION APPROXIMATION



$$q = m \cdot c \cdot \Delta T$$

$$q_2 = \rho \cdot A_2 \cdot t \cdot c \cdot T_2$$

$$q_1 = \rho \cdot A_1 \cdot d \cdot c \cdot T_1$$

$$\boxed{\Delta T = \frac{Q}{\rho \cdot c}\left(\frac{1}{d} - \frac{1}{t}\right)}$$

$\Delta T = T_1 - T_2$

$Q = q/A$

CONTRAST PROPERTIES

$$\Delta T = \frac{Q}{\rho \cdot c}\left(\frac{1}{d} - \frac{1}{t}\right)$$

1. THE CONTRAST (ΔT) INCREASES LINEARLY WITH THE AMOUNT OF DEPOSITED ENERGY PER UNIT AREA (Q).

2. THE HIGHER THE SPECIFIC HEAT-DENSITY OF A MATERIAL ($\rho c\uparrow$) THE SMALLER THE PEAK CONTRAST ($\Delta T\downarrow$)

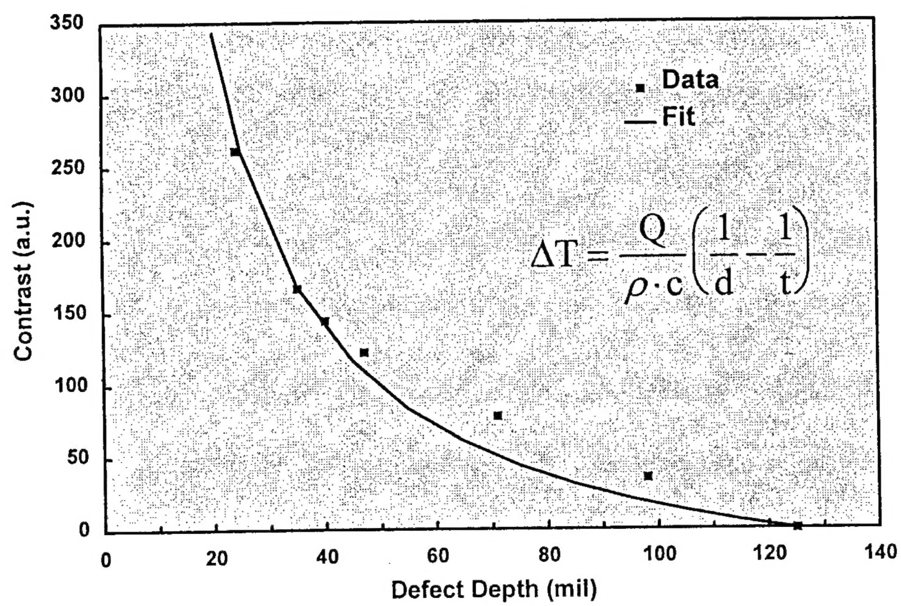
3. THE CLOSER THE DEFECT TO THE SURFACE ($d \rightarrow 0$) THE HIGHER THE PEAK CONTRAST ($\Delta T \rightarrow \infty$).

4. AS THE DEFECT DEPTH APPROACHES THE PANEL THICKNESS ($d \rightarrow t$) THE CONTRAST VANISHES ($\Delta T \rightarrow 0$).

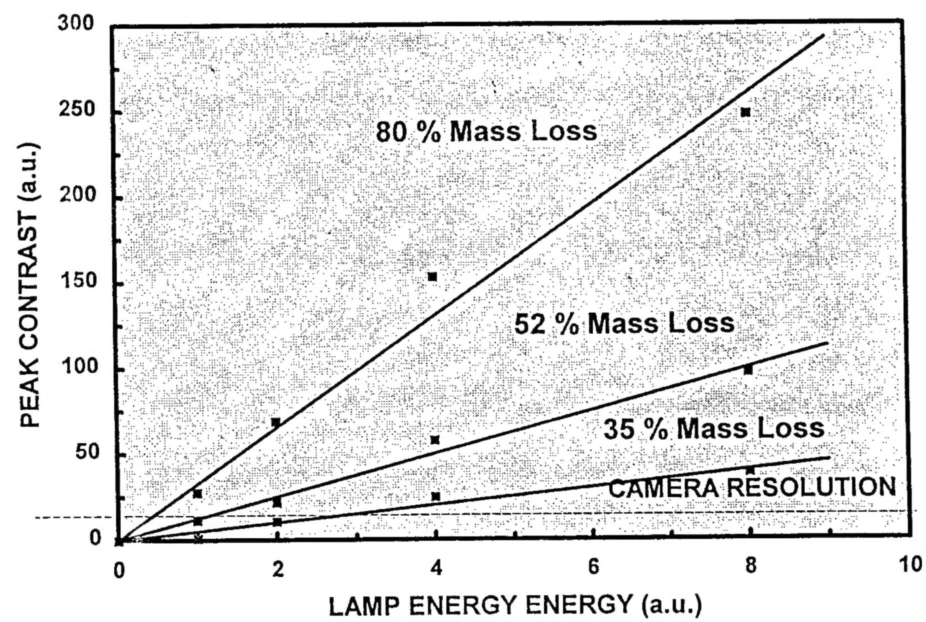
5. FOR A GIVEN DEFECT DEPTH D, THE THICKER THE PANEL ($t \rightarrow \infty$) THE LARGER THE CONTRAST ($\Delta T \rightarrow Q/\rho c d$).

SIMPLE MODEL CORRELATION
(no lateral heat flow)

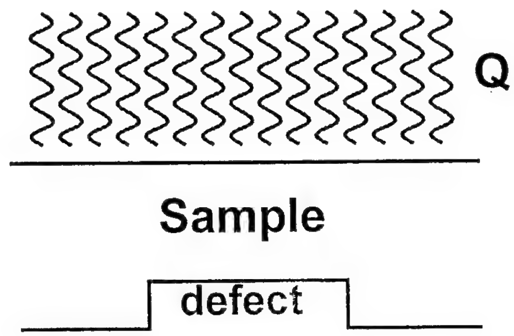
CONTRAST vs DEPTH

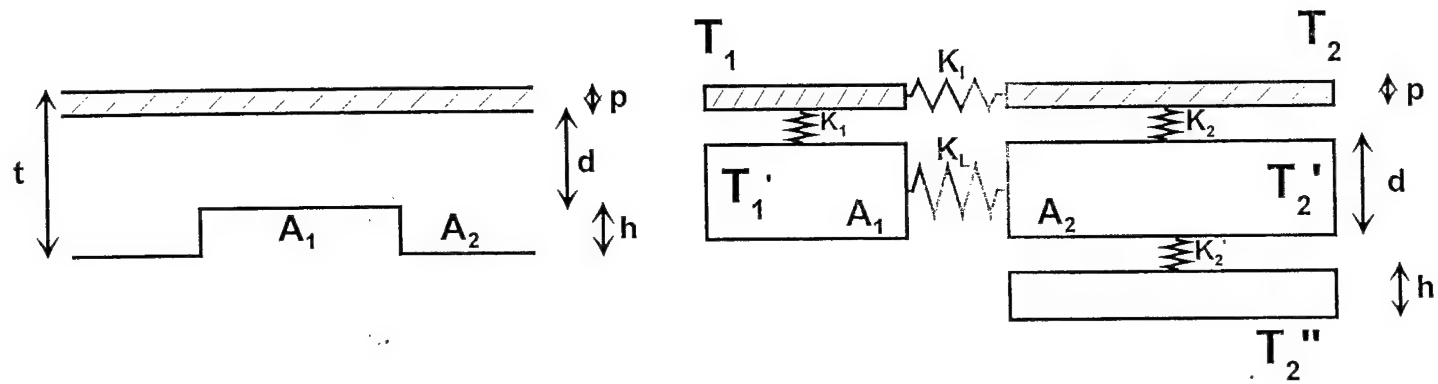


DEPTH OF RESOLUTION vs ENERGY



SIMPLE FINITE ELEMENT APPROXIMATION





$$\rho \cdot A_1 \cdot p \cdot c \cdot \frac{dT_1}{dt} = k \cdot A_1 (T_1' - T_1) + k_L \cdot A_p (T_2 - T_1)$$

$$\rho \cdot A_2 \cdot p \cdot c \cdot \frac{dT_2}{dt} = k \cdot A_2 (T_2' - T_2) + k_L \cdot A_p (T_1 - T_2)$$

$$\vdots$$

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2''}{dt} = k \cdot A_2 (T_2' - T_2'')$$

k = Effective Contact Normal Thermal Conductivity

k_L = Effective Contact Lateral Thermal Conductivity

MODEL ASSUMPTIONS

- THE ENERGY "Q" IS ABSORBED BY A THIN LAYER OF THICKNESS "p". THE EXPRESSIONS DERIVED IN THIS WORK ARE DERIVED IN THE LIMIT WHEN " $p \to 0$ "
- NO ENERGY IS DISSIPATED RADIATEVILY OR CONVECTIVELY TO THE SORROUNDING ENVIRONMENT
- THE CONDUCTANCE "K" BETWEEN ELEMENTS CAN HAS BEEN EXPRESSED AS " $K = k\, A/l$ ". THE LATERAL AND NORMAL CCONDUCTIVITIES ARE ASSUMED TO BE DIFFERENT

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LATERAL HEAT FLOW EFFECTS
(effective contact conductivity model)

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$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left(e^{-\frac{a}{d}\frac{k}{\rho c}t} - e^{-\frac{1+r}{d}\frac{k}{\rho c}t} \right)$$

$$t_{peak} = \frac{\rho c}{k} \frac{d}{1 - a + r} \ln \frac{1 + r}{a}$$

$$\boxed{\Delta T_{peak} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \underbrace{\left\{ \frac{t_o}{a \cdot h} \left[\frac{a \cdot h}{t_o} \right]^{\frac{1}{1-\frac{a \cdot h}{t_o}}} \right\}}_{\text{LATERAL HEAT FACTOR}}}$$

$$a = \frac{k_L \cdot A_L}{k_n \cdot A_n}$$

$$h = t - d$$

$$r = \frac{d}{t - d}$$

THERMAL CONTRAST PREDICATIONS (effective contact conductivity model)

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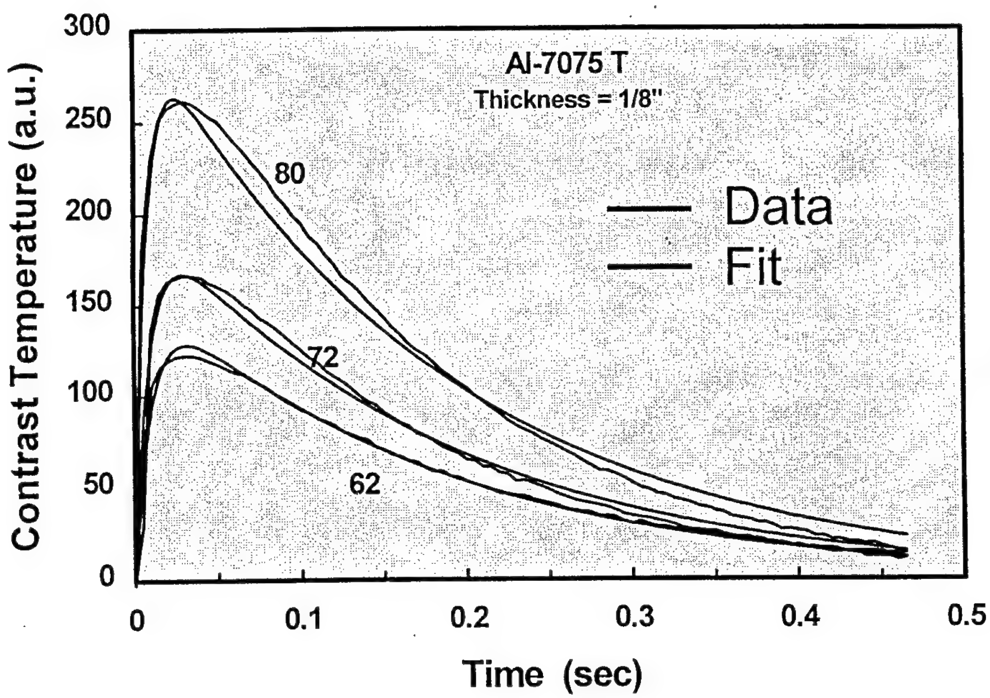
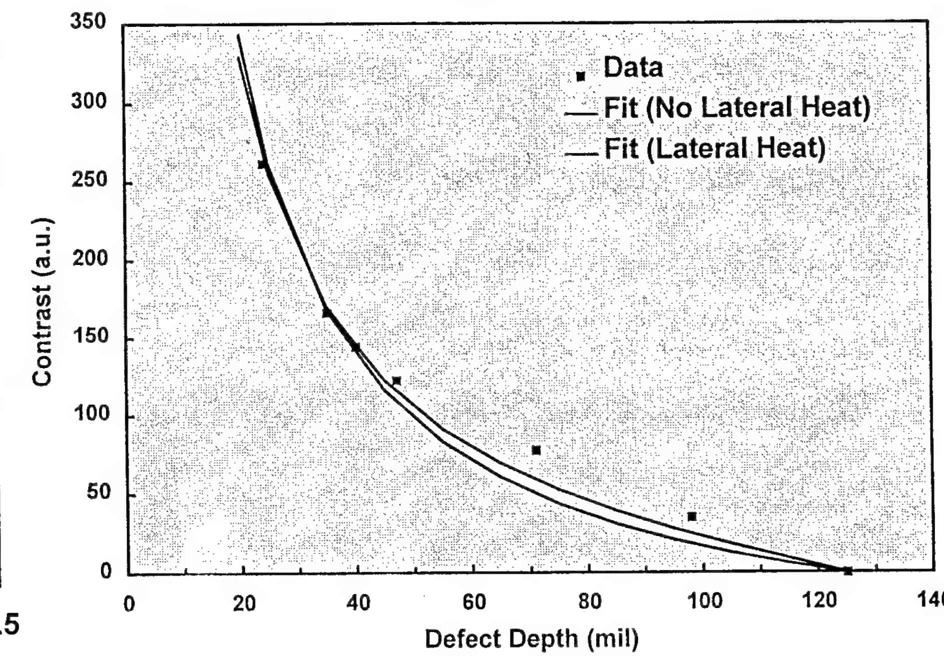
Fit of Contrats Curves



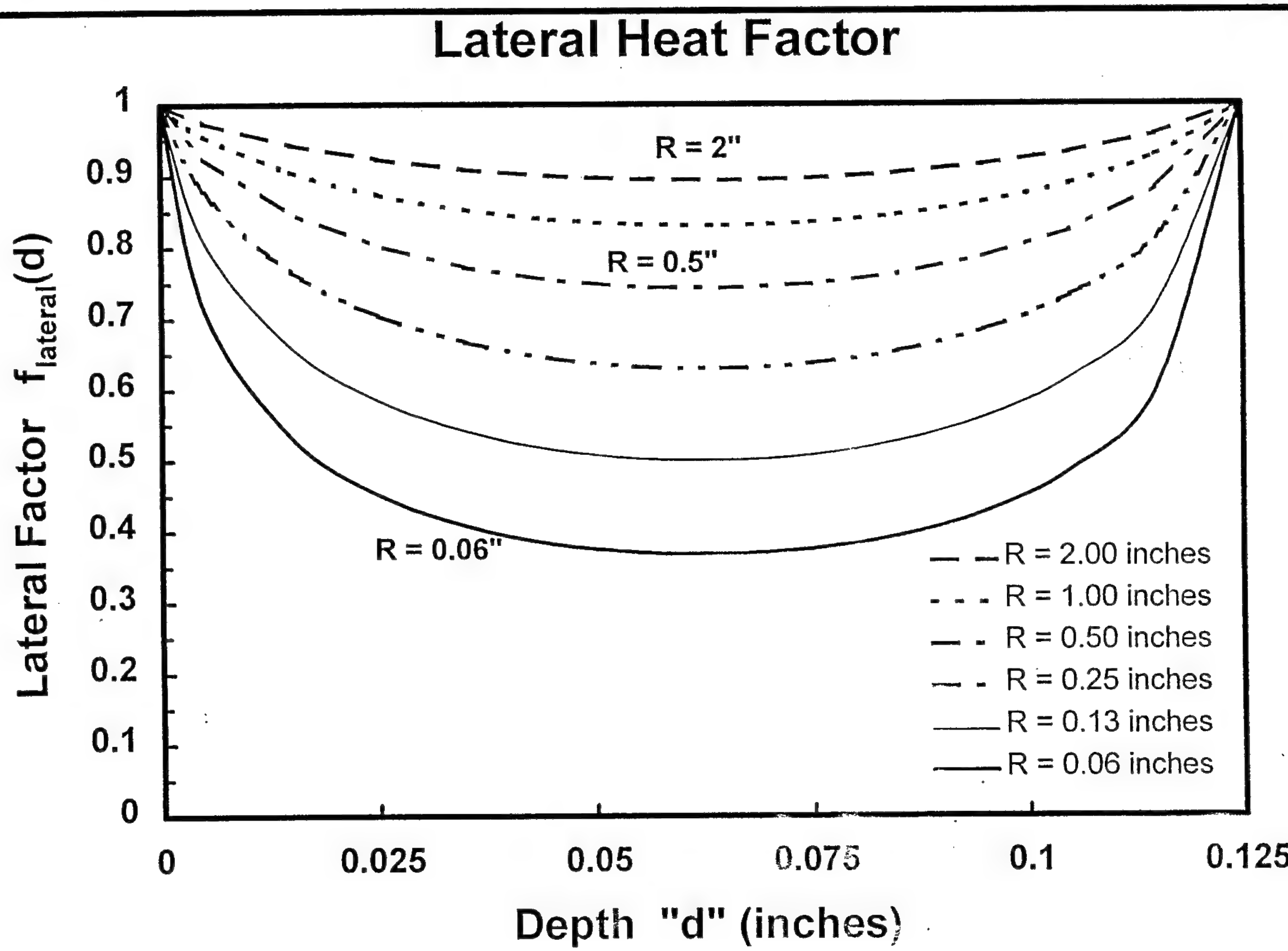
CONTRAST vs DEPTH



$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left(e^{-\frac{a}{d}\frac{k}{\rho c}t} - e^{-\frac{1+r}{d}\frac{k}{\rho c}t} \right)$$

$$\Delta T_{peak} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \left\{ \frac{t_o}{a \cdot h} \left[\frac{a \cdot h}{t_o} \right]^{\frac{1}{1 - \frac{a \cdot h}{t_o}}} \right\}$$

LATERAL HEAT FACTOR
(effective contact conductivity model)



$$\Delta T_{peak} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \left\{ \frac{t_o}{a \cdot h} \left[\frac{a \cdot h}{t_o} \right]^{\frac{1}{1 - \frac{a \cdot h}{t_o}}} \right\}$$

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CONTRAST PROPERTIES
(specific thermal conductivity)

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$$\Delta T_{peak} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \left\{ \frac{t_o}{a \cdot h} \left[\frac{a \cdot h}{t_o}\right]^{\frac{1}{1-\frac{a \cdot h}{t_o}}} \right\}$$

$$a = \frac{k_L \cdot A_L}{k_n \cdot A_n}$$

$$h = t - d$$

1. THE CONTRAST (ΔT) INCREASES LINEARLY WITH THE AMOUNT OF DEPOSITED ENERGY PER UNIT AREA (Q).

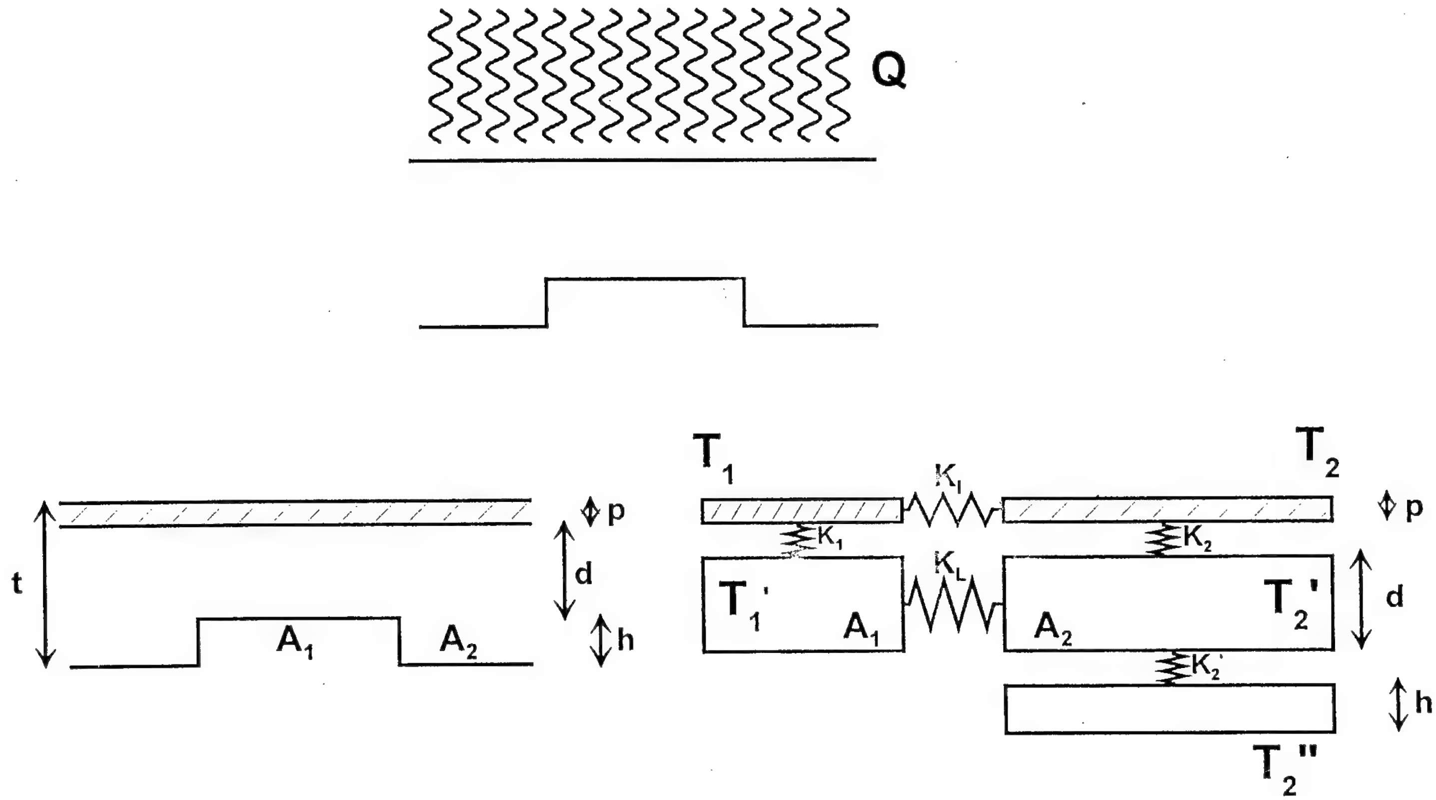
2. THE HIGHER THE SPECIFIC HEAT-DENSITY OF A MATERIAL ($\rho c\uparrow$) THE SMALLER THE PEAK CONTRAST ($\Delta T \downarrow$)

3. THE CLOSER THE DEFECT TO THE SURFACE ($d \rightarrow 0$) THE HIGHER THE PEAK CONTRAST ($\Delta T \rightarrow \infty$).

4. AS THE DEFECT DEPTH APPROACHES THE PANEL THICKNESS ($d \rightarrow t$) THE CONTRAST VANISHES ($\Delta T \rightarrow 0$).

5. FOR A GIVEN DEFECT DEPTH D, THE THICKER THE PANEL ($t \rightarrow \infty$) THE LARGER THE CONTRAST ($\Delta T \rightarrow Q/\rho cd$).

LATERAL HEAT FLOW MODEL
(specific thermal conductivity)



$$\rho \cdot A_1 \cdot p \cdot c \cdot \frac{dT_1}{dt} = k \cdot \frac{A_1}{p+d}(T_1' - T_1) + k_L \cdot \frac{A_p}{R}(T_2 - T_1)$$

$$\rho \cdot A_2 \cdot p \cdot c \cdot \frac{dT_2}{dt} = k \cdot \frac{A_2}{p+d}(T_2' - T_2) + k_L \cdot \frac{A_p}{R}(T_1 - T_2)$$

$$\vdots$$

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2''}{dt} = k \cdot \frac{A_2}{h+d}(T_2' - T_2'')$$

k = Thermal Conductivity

k_L = Lateral Thermal Conductivity

LATERAL HEAT FLOW MODEL COMPARISON

SPECIFIC THERMAL CONDUCTIVITY

$$K = \frac{k \cdot A}{l}$$

$$\Delta T(t) = \frac{Q}{\rho c \cdot t_o} \frac{h}{(d - a \cdot h)} \left(e^{-a \frac{k}{\rho c d^2} t} - e^{-\frac{d}{h} \frac{k}{\rho c d^2} t} \right)$$

$$t_{peak} = \frac{\rho c}{k} d^2 \frac{h}{a \cdot h - d} \ln \frac{a \cdot h}{d}$$

$$\boxed{\Delta T_{peak} = \frac{Q}{\rho c} \left(\frac{1}{d} - \frac{1}{t_o} \right) \cdot \left\{ \frac{d}{a \cdot h} \left[\frac{a \cdot h}{d} \right]^{\frac{1}{1 - \frac{a \cdot h}{d}}} \right\}}$$

$$a = \frac{k_L \cdot A_L \cdot d}{k_n \cdot A_n \cdot R}$$

EFFECTIVE CONTACT CONDUCTIVITY

$$K = k \cdot A$$

$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left(e^{-\frac{a}{d} \frac{k}{\rho c} t} - e^{-\frac{1+r}{d} \frac{k}{\rho c} t} \right)$$

$$t_{peak} = \frac{\rho c}{k} \frac{d}{1 - a + r} \ln \frac{1 + r}{a}$$

$$\boxed{\Delta T_{peak} = \frac{Q}{\rho c} \left(\frac{1}{d} - \frac{1}{t_o} \right) \cdot \left\{ \frac{t_o}{a \cdot h} \left[\frac{a \cdot h}{t_o} \right]^{\frac{1}{1 - \frac{a \cdot h}{t_o}}} \right\}}$$

$$a = \frac{k_L \cdot A_L}{k_n \cdot A_n}$$

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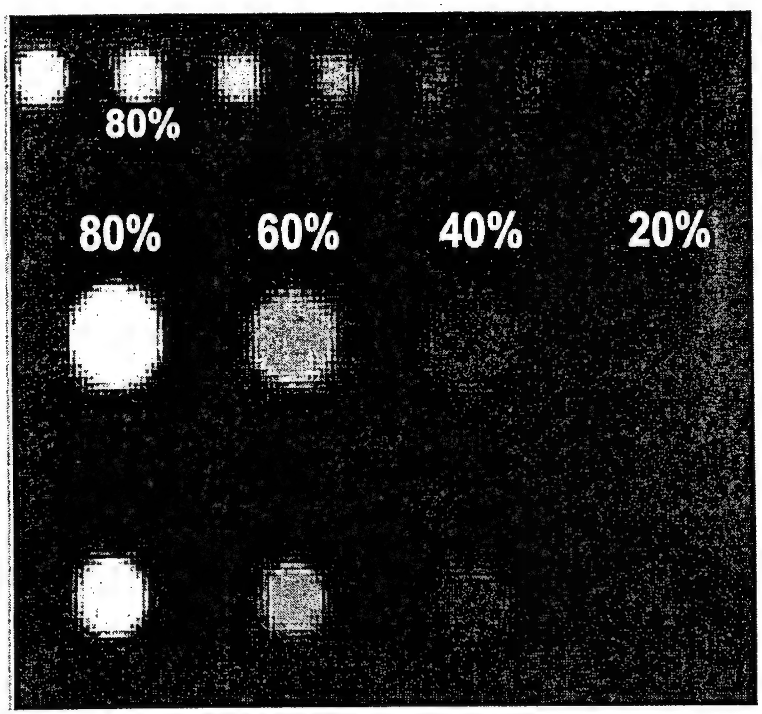
EXPERIMENTAL DATA
(80% mass removal)

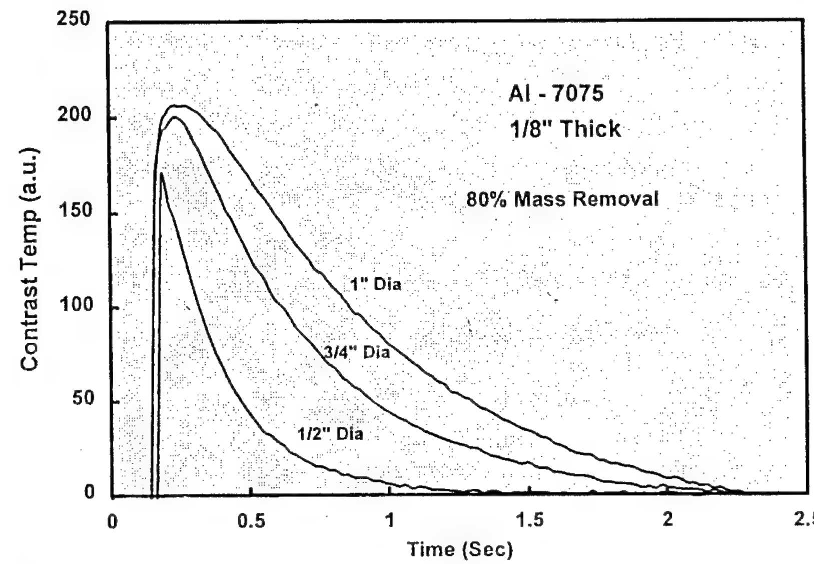
NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

1/2" →

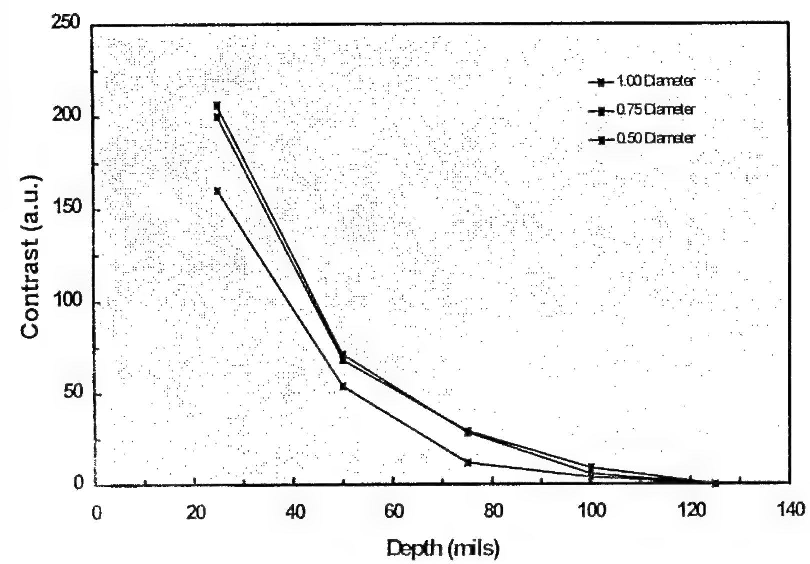
1" →

3/4" →





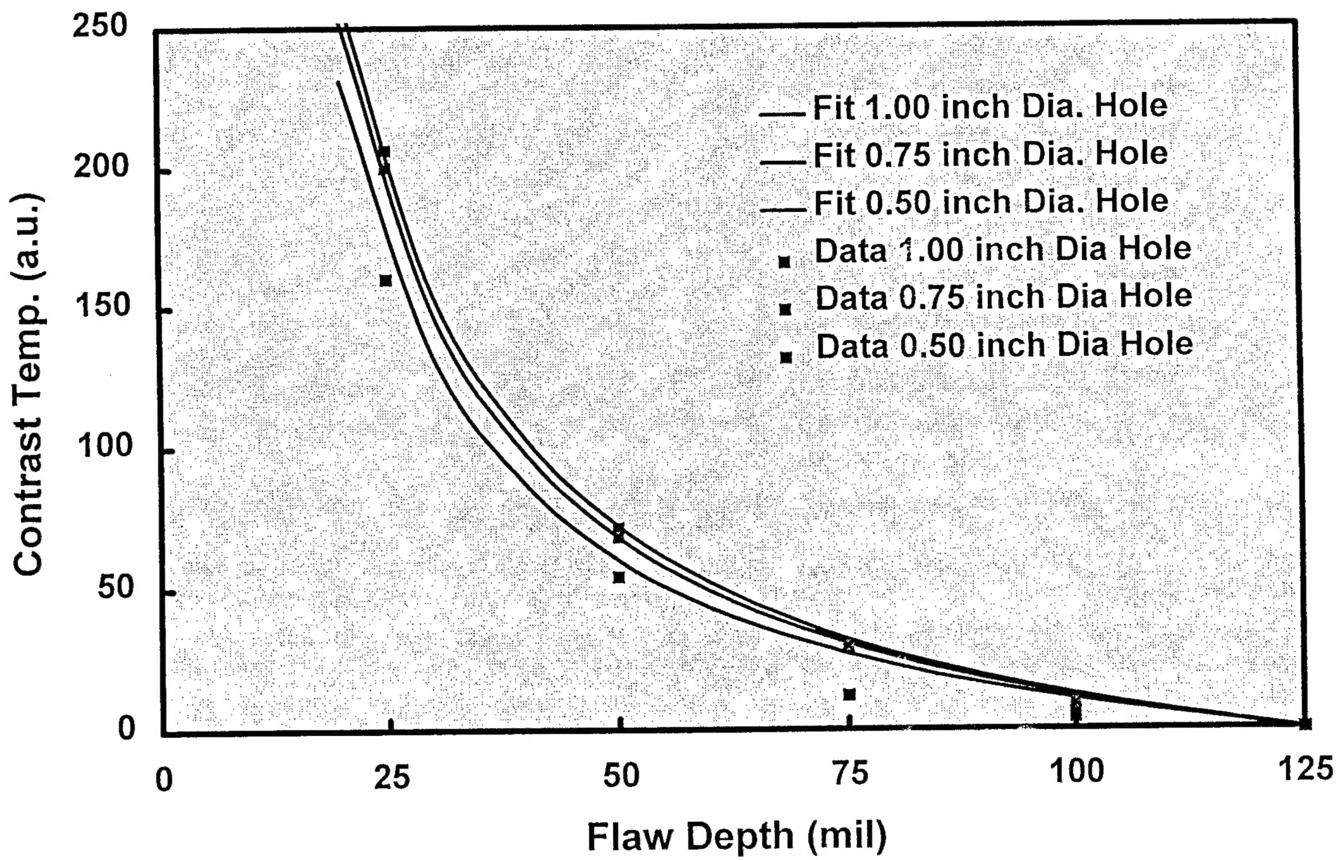
PEAK TEMP. vs DEPT



MODEL CORRELATION
(effects of defect size)

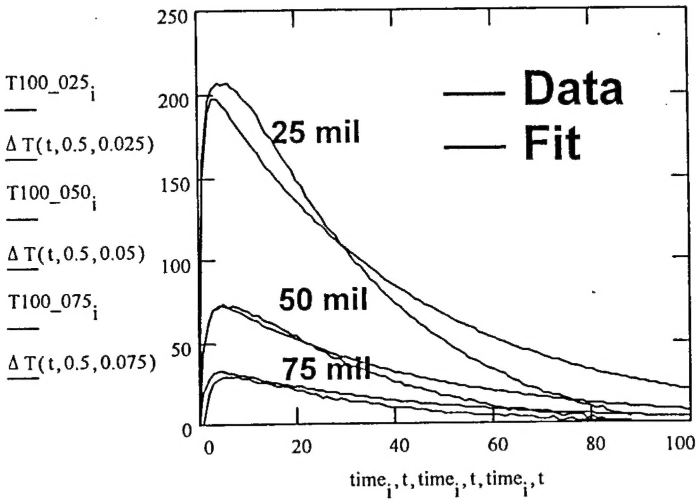
$$\Delta T_{peak} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \left\{ \frac{d}{a \cdot h}\left[\frac{a \cdot h}{d}\right]^{\frac{1}{1-\frac{a \cdot h}{d}}} \right\}$$

Effects of Radii

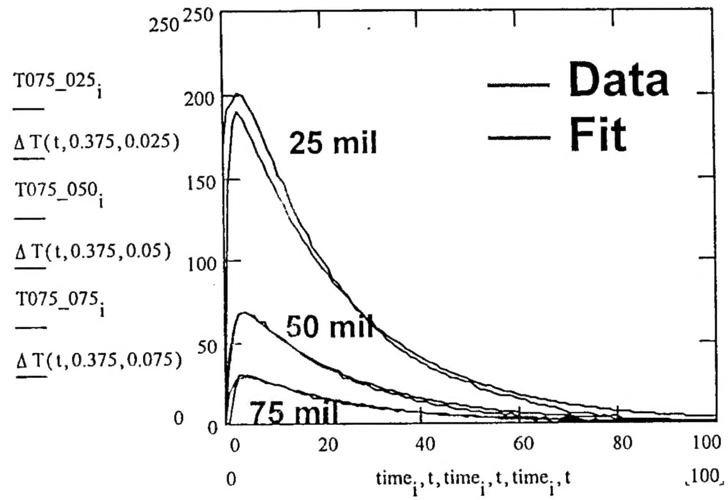


MODEL TIME-RESPONSE PREDICTIONS (varying defect sizes and locations)

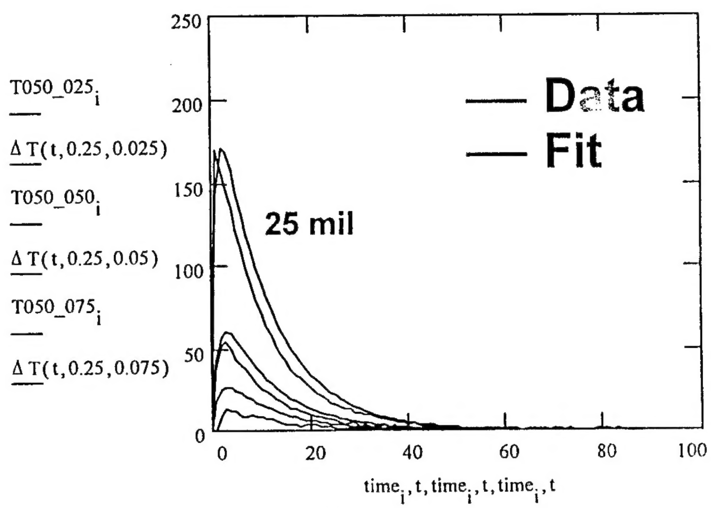
Dia = 1.00"



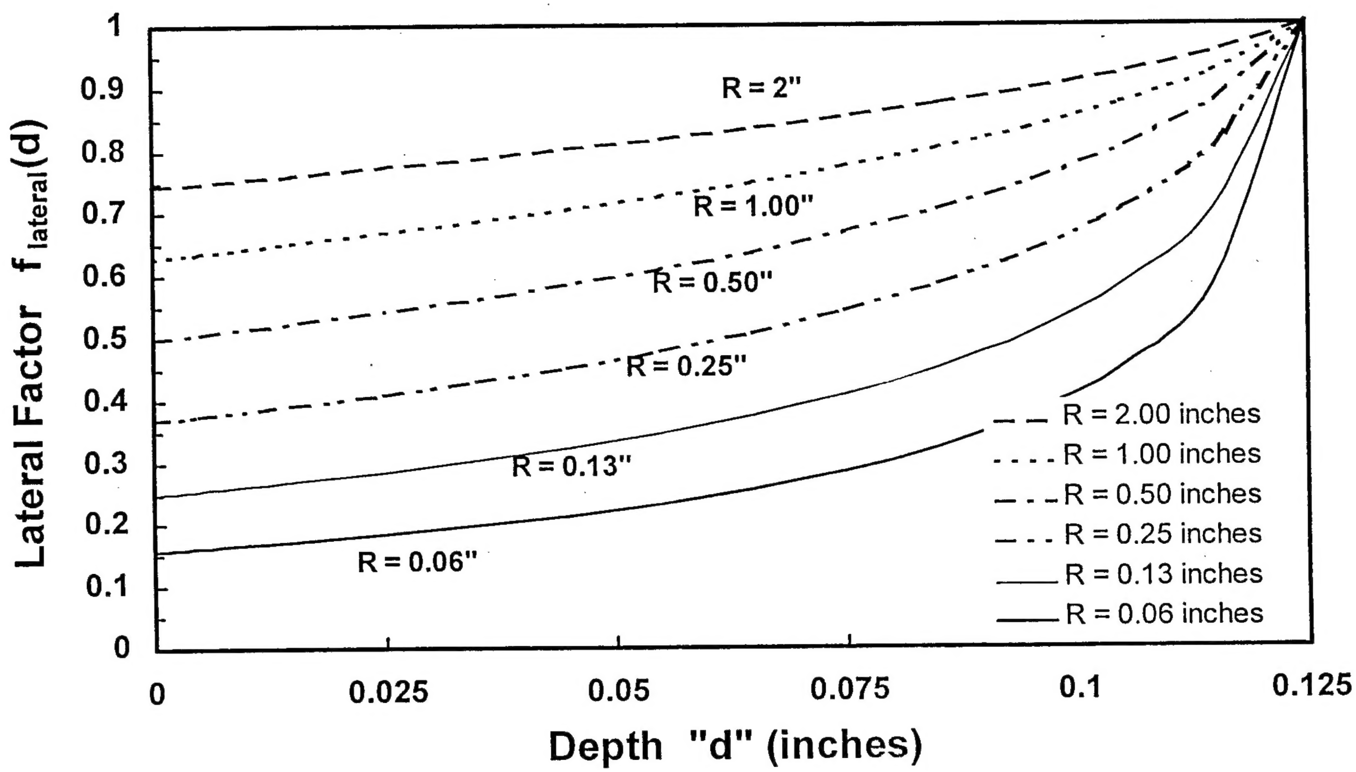
Dia = 0.75"



Dia = 0.50"



Lateral Heat Factor



$$\Delta T_{peak} = \frac{Q}{\rho c}\left(\frac{1}{d} - \frac{1}{t_o}\right) \cdot \underline{\left\{ \frac{d}{a \cdot h}\left[\frac{a \cdot h}{d}\right]^{\frac{1}{1-\frac{a \cdot h}{d}}} \right\}}$$

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SUMMARY AND CONCLUSIONS

NAVAL AIR SYSTEMS COMMAND RESEARCH & ENGINEERING

- Calorimetric model was developed to predict thermal contrast.
- Model accounts for defect size, location, and lateral conductivity effects.
- Calorimetric model correlates well with experimental results.
- Anisotropic thermal conductivity can be modeled.
- Model accuracy should improve as the element mesh is refined.